Spatial Dependence of a Piezo-Magnetic MEMS harvester Relative to the Electromagnetic Source

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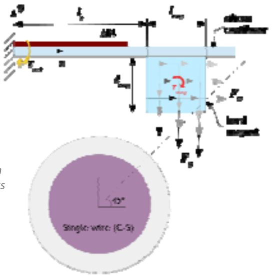
Introduction

- A silicon-based, MEMS device with a piezoelectric layer and integrated magnet is presented for magnetic to electrical transduction.
- When placed in the field of a conductor carrying an alternating current, electromagnetic forces on the magnet cause the cantilever to vibrate in its first mode.
- The thin piezoelectric film (AlN) converts the strain in the oscillating beam to electrical charge.
- The cantilever structure can be configured either as an energy harvester to harvest power from an AC power line or as an AC current sensor.
- The positioning of the transducer with respect to the AC conductor is critical in both scenarios.
- This work considers the effect of the relative position of the transducer with respect to the wire on the resulting electromagnetic forces and torques driving the device so that the harvested power and/or sensor sensitivity can be optimized.

Theory



Schematic shows the lateral and vertical forces acting on a cantilever magnet that is in close proximity to a current carrying conductor. Also shown is the magnetic torque that acts to rotate the magnet into the electromagnetic field.

- The net torque at the beam anchor of a stiff beam is given by the sum of the individual torque components:

justifiably neglected in most cases

only $\tau(F_y)$ considered previously

$$\tau_{net} = \tau(F_x) + \tau(F_y) + \tau_{mag}$$

Shown here that τ_{mag} cannot be omitted from calculations

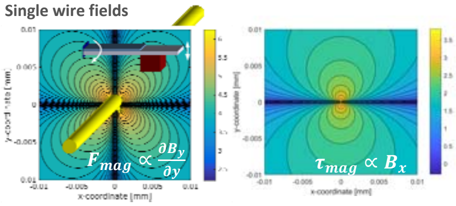
- The force on a magnet in a non-uniform electromagnetic field gradient is given by the gradient of the field:

$$F_{mag} = F_x\mathbf{i} + F_y\mathbf{j} = \oiiint \nabla(\boldsymbol{M}.\boldsymbol{B})\,dV$$

- And τ_{mag}, the torque that tends to rotate the magnet into the electromagnetic field is given by:

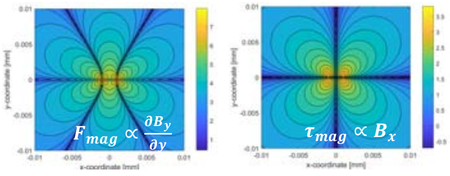
$$\tau_{mag} = \oiiint \boldsymbol{M} \times \boldsymbol{B}\,dV$$

Single wire fields



Contour plots for single wire show that $\boldsymbol{F_{mag}}$ is maximized when magnet is at 45° to the wire whereas τ_{mag} is maximized when magnet is directly over wire.

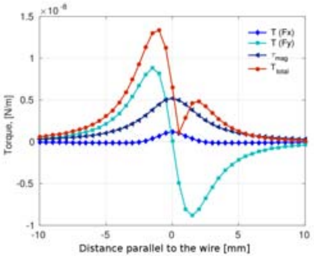
Two-wire fields



Contour plots show that $\boldsymbol{F_{mag}}$ is maximized when magnet is directly over two-wire cord whereas τ_{mag} is maximized when magnet is at 45° to two-wire cord.

> The magnetic torque, $\boldsymbol{\tau_{mag}}$, becomes significant for thick magnets and cannot be omitted from the analysis.

Single Wire

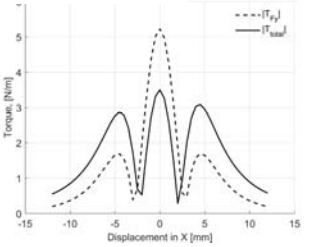


Torque versus relative location of the magnet to the wire. The cantilever is 8 mm long and 25 μm thick with a 1 mm cube magnet located mid-way along the beam. A gap of 2 mm between the magnet and the wire was assumed.

Outcome for Single Wire:

- Inclusion of $\boldsymbol{\tau_{mag}}$
  - Asymmetry in the net torque (red line)
  - Shift in the minimum

Two Wire



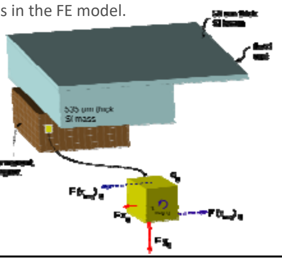
Torque versus relative location of the magnet to a two wire cord. Dashed line shows result if only $\boldsymbol{F_{mag}}$ is taken in account; solid line shows outcome when all torque contributions are accounted for.

Outcome for Two Wire Cord:

- Inclusion of $\boldsymbol{\tau_{mag}}$
  - See lower than expected output when magnet is positioned directly over cord
  - Some asymmetry in result.

Finite Element Modelling

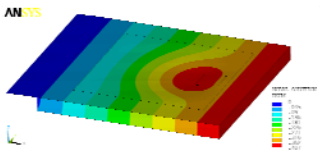
- The theoretical work above assumed an infinitely stiff beam. In reality the beam is just tens of microns thick
  - Localized beam bending must be considered.
- The forces applied to the discretized magnet were first calculated in Matlab and then transferred to the appropriate nodes in the FE model.



Static and dynamic analyses were used to evaluate the warping and tip displacement of the beam.

Results

- Result of the FE simulation show warping of the thin beam due to the magnetic torque on the magnet.



- Dynamic FE analyses show little deviation from the analytical results
- The result is in contrast to the result that would have been obtained if only the vertical force component of the electromagnetic vector were used.
- The theory/FE simulations were validated experimentally both with laser vibrometry and electrical measurements.

Laser Vibrometery Measurements:

- A 1 mm cube magnet was attached to the cantilever beam using a very thin epoxy layer.
- The cantilever was then passed over a electrical wire carrying an AC signal.
- The frequency of the AC signal was set to equal the natural resonance of the beam.
- The tip displacement of the cantilever was measured using a dynamic interferometer for each position of the magnet relative to the wire.

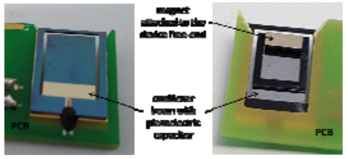
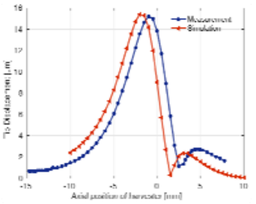


Photo shows a cantilever on a board with an attached magnet.

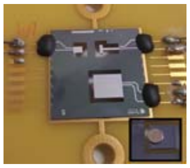
- Excellent agreement between measurement and simulation was observed in the shape of the displacement versus magnet location curve.

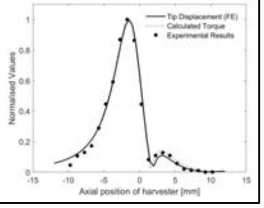


Comparison between measurement and simulation results for a 8mm long cantilever with a 1mm cube magnet attached mid-way along the beam length. The result shows excellent agreement and confirms that the inclusion of the magnetic torque in the analysis is critical.

Electrical Measurements:

- A 1 mm diameter, 0.5 mm thick, circular magnet attached to a 6 mm long was used for the electrical measurements.
- The current output from the piezoelectric capacitor was monitored as the cantilever-magnet assembly was passed over a current carrying single wire conductor.
- The measured result shows excellent agreement with the analytical and FE data.





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